Geochemistry Geophysics Geosystems G3
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society

Article
Volume 9, Number 8
9 August 2008
Q08O11, doi:10.1029/2008GC002010
ISSN: 1525-2027

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Depth-shifting cores incompletely recovered from the upper oceanic crust, IODP Hole 1256D

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[1] Seafloor drilling operations, especially those in crustal rocks, yield incomplete recovery of drilled sections, and depths of the recovered core pieces are assigned with some uncertainty. Here we present a new depth-shifting method that is simple and rapid, requires little subjective input, and is applicable to any core-log integration problem where sufficient comparable data have been collected in both the open hole and from the recovered core. Over the depth range for which both core and log data have been collected, an automatic algorithm selected the best new depth for each piece. The criteria for determining the best depth were as follows: (1) find new depths for as many pieces as possible, and (2) minimize the difference between core density and log density. In this study, depth-shifting is applied at Integrated Ocean Drilling Program (IODP) Hole 1256D, which is our first opportunity to study a section of intact, in situ upper ocean crust drilled down to gabbro. The new depths significantly improve the agreement between an independent data set and the logging record.

Components: 6350 words, 8 figures, 2 tables.

Keywords: ocean drilling; core-log integration; IODP Site 1256.

Index Terms: 3036 Marine Geology and Geophysics: Ocean drilling; 3035 Marine Geology and Geophysics: Midocean ridge processes; 5199 Physical Properties of Rocks: General or miscellaneous.

Received 29 February 2008; **Revised** 14 May 2008; **Accepted** 20 June 2008; **Published** 9 August 2008.

Gilbert, L. A., and A. Burke (2008), Depth-shifting cores incompletely recovered from the upper oceanic crust, IODP Hole 1256D, *Geochem. Geophys. Geosyst.*, *9*, Q08O11, doi:10.1029/2008GC002010.

Theme: Formation and Evolution of Oceanic Crust Formed at Fast Spreading Rates

1. Introduction

[2] Significant effort has been spent, for the last four decades, on scientific drilling into the ocean floor. Geophysical, geochemical, petrologic, and structural data collected from both recovered cores and logged in the drilled holes have been used to make many significant advances in our understanding of both the ocean crust and overlying sediments. However, in seafloor drilling operations (especially those in crustal rocks) the recovery of cores is generally incomplete and depths of recov-

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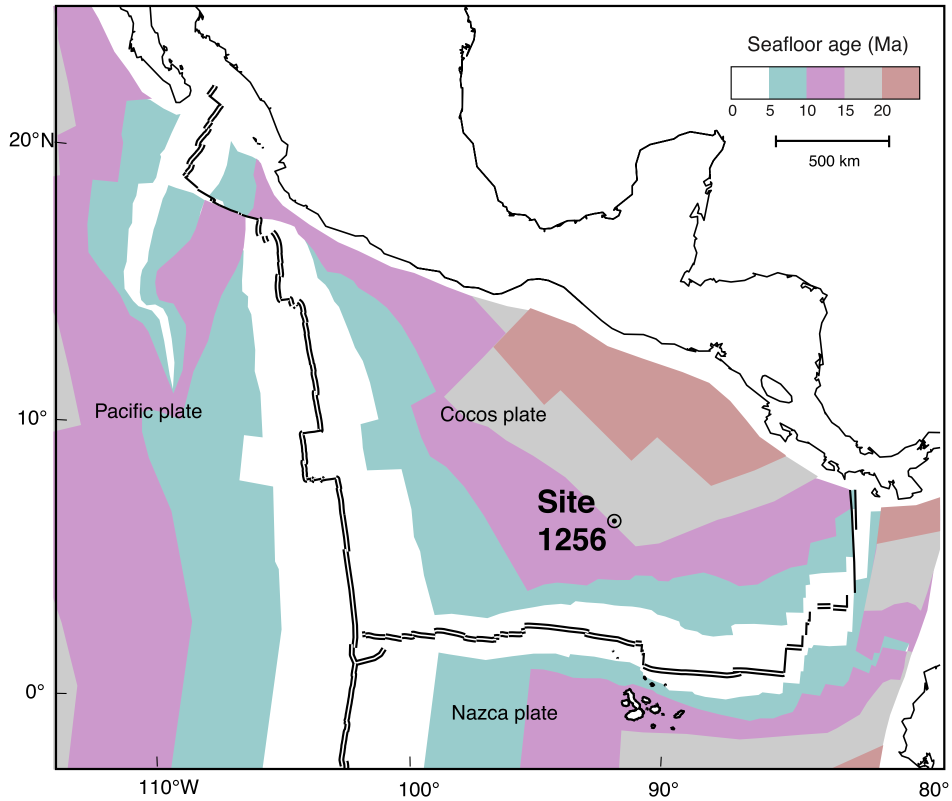

Figure 1. Location of IODP Site 1256. (Modified from *Teagle et al.* [2006].)

ered core pieces are assigned with some uncertainty. Detailed studies on the recovered cores are at a fine scale, but only represent a fraction of the total lithologic column. Logging data give us a more complete geophysical view of intact crust, but at coarser detail and with the limitations of remote measurement. The ability to perfectly integrate information from both the recovered core pieces and the logging of intact holes, would be a significant advance toward understanding the magmatic, tectonic, and hydrothermal processes that control the formation and evolution of ocean crust.

[3] The goal of this work is to improve the depth assignments for recovered cores at the meter to centimeter scale. Currently, the Integrated Ocean Drilling Program (IODP) routinely assigns the top of a given recovered core to the top of the drilled interval, and shifts all separate pieces within that core to the minimum possible depth below the top piece. This depth assignment method can lead to depth uncertainty of up to several meters or more. For example, if 50 cm of material is recovered from a 9 m drilled core (not an uncommon recovery), there is an 8.5 m uncertainty in the true depth of any recovered piece. Our primary goal here is to improve the initial depth assignment and thus facilitate further core-log integration at ODP/IODP Hole 1256D, the first hole to reach gabbro through intact in situ ocean crust [*Wilson et al.*, 2006]. We also explain our method generally, so that it may be applied to other drilled holes.

[4] In the past, significant effort has been directed at integrating core and logging data from ocean drilling. Although few holes have penetrated more than 200 m into igneous rock [*Teagle et al.*, 2006], various methods of core-log integration have been done at ODP Holes 395A, 504B, and 735B, in the Atlantic, Pacific, and Indian Ocean, respectively [*Agrinier and Agrinier*, 1994; *Bartetzko et al.*, 2001; *Haggas et al.*, 2001]. Some studies have taken a probabilistic approach [e.g., *Agrinier and Agrinier*, 1994]. Other efforts at core-log integration focus on the average properties for a given interval. For example, discriminant analysis uses statistical software to classify different rock types (e.g., massive basalts, pillow basalts, etc.) of a depth interval based on electrofacies: a set of responses that are unique to a rock type [e.g., *Bartetzko et al.*, 2001]. Discriminant analysis of electrofacies can provide a more complete lithostratigraphic column than the column based solely on core pieces, but does not address the problem of

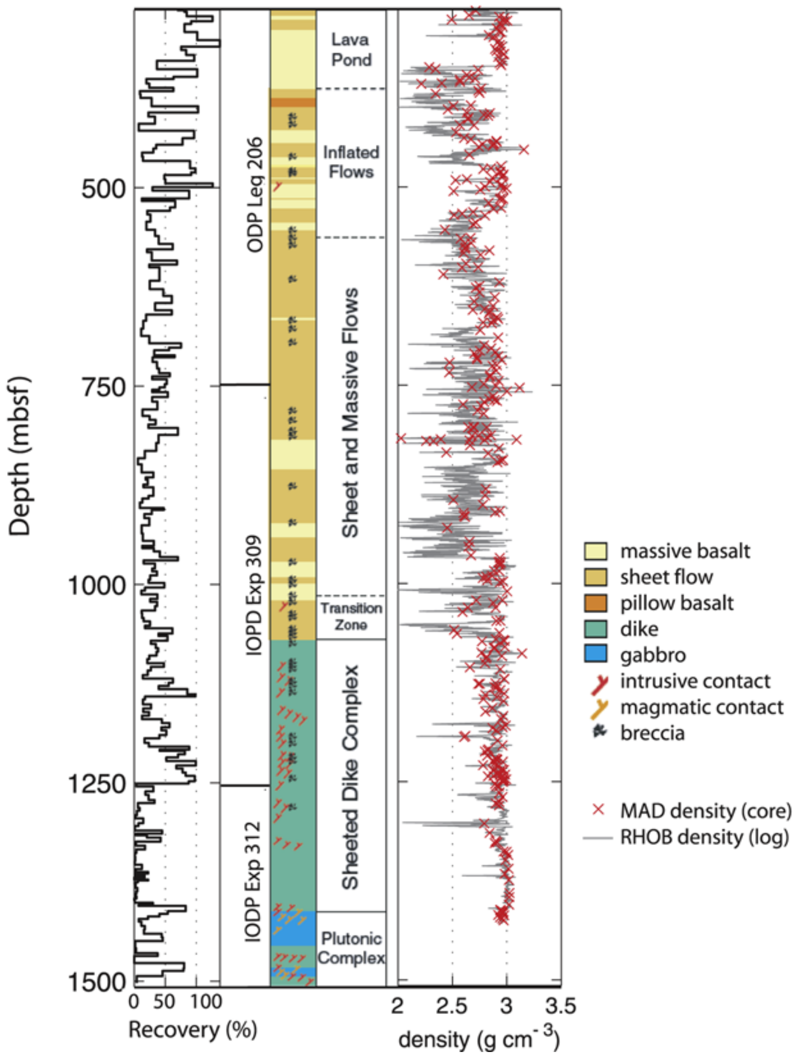

Figure 2. IODP Hole 1256D core recovery revised using tide corrections in Table 1, lithostratigraphic column, and depth-shifted MAD core data superimposed on RHOB log data. (Modified from *Teagle et al.* [2006].)

adjusting the depth of individual pieces. Other researchers have used high-resolution image analysis of recovered cores and from the corresponding hole using structural and other features [*Lofts and Bristow*, 1998; *Haggas et al.*, 2001]. However, the image analysis method provides new depths for relatively few of the core pieces. Our method takes advantage of the repeat measurements of physical properties at different scales on the recovered core and with logging tools in the open hole to produce an improved depth record for the core pieces throughout the logged interval.

[5] Our depth-shifting method can be employed in any drill hole where there is one or more comparable measurements on both the recovered core and the downhole wireline logs. In this study we use density acquired in different ways for the recovered core and within the open hole. We explain our method using core density and log density, but our method could be applied more broadly, where density measurements are substituted by another property.

2. Data Acquisition

[6] Data were acquired both from recovered cores and logged from within IODP Hole 1256D in the middle of the Cocos Plate, 800 km west of Panama (06°44.1631′N × 091°56.0612′W; Figure 1). Drilling operations penetrated a total of 1507 m below seafloor (mbsf) with about 37% recovery (Figure 2) and logged to 1432 mbsf at Hole 1256D during ODP Leg 206 and IODP Expeditions 309 and

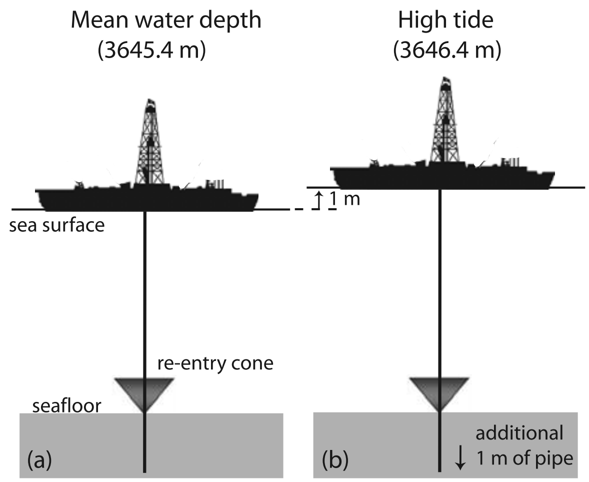

Figure 3. Tidal effect. At high tide (Figure 3b), an additional 1 m of core is extended to reach the same depth below seafloor as drilling during mean tidal height (Figure 3a). Mean water depth at IODP Hole 1256D is 3645.4 mbsf, and mean tidal range is ~2 m. Cores drilled during high tides required more pipe out, and thus the tidal height was subtracted from the pipe length to calculate a depth record normalized to mean tidal height.

312 [*Teagle et al.*, 2006]. Both the core data (Integrated Ocean Drilling Program and Texas A&M University, available at http://www-odp.tamu.edu/database/, accessed 31 December 2007) and log data (Integrated Ocean Drilling Program and Lamont Doherty Earth Observatory, available at http://iodp.ldeo.columbia.edu/DATA/, accessed 31 December 2007) for this study are now publicly available online. We used three physical property data sets: two for the depth-shifting process and an additional one to evaluate the post-shift core-log agreement.

[7] From the recovered cores we used the gamma ray density (GRA) and moisture and density (MAD) data sets. GRA data were acquired every 2.5 cm on full-round cores using a ^{137}Cs gamma ray source (660 keV) and a standard NaI scintillation detector on board the scientific drilling vessel *JOIDES Resolution*, before the cores were split in half for further analysis [e.g., *Blum*, 1997]. GRA densities were volume-corrected for the average diameter of the core.

[8] From the half-cores, crack-free 2 cm by 2 cm by 2 cm cubes were cut for MAD analysis at variable intervals (one per core, wherever possible). MAD bulk density was calculated from weight (wet and dry) and volume, which were measured aboard the *JOIDES Resolution* with a Scintech-202 electronic dual balance (±0.01 g) and a Quantachrome Pentapycnometer (±0.01 cm^3), respectively. An additional 105 MAD cubes were evaluated for density using identical methods in the Williams-Mystic laboratory with a Denver Instruments M-220D electronic balance (±0.001 g) and another Quantachrome Pentapycnometer (±0.01 cm^3). Repeat measurements of several MAD cubes in both laboratories gave the same results, within instrument precision.

[9] From the open hole, we used bulk density (RHOB) acquired with the Hostile Environment Litho-Density Sonde on the triple-combo string. This tool and its use in Hole 1256D are described by *Teagle et al.* [2006]. RHOB density was recorded every 15.24 cm downhole.

3. Data Reduction

[10] We only reduced data from 276 to 1432 mbsf, the depth range from which both core recovery and logging data were collected, although we tide-corrected every core. During the ~3 hours (190 ± 30 min) of drilling a typical core at 1256D, the semidiurnal ocean tide at Hole 1256D can vary up to ~1 m (Figure 3); the average tidal range is ~2.1 m. We corrected the depths of the top and bottom of each core using Oregon State University's TPXO6.2 tide predictions [*Egbert and Erofeeva*, 2002]. At the time drilling started for a core, we subtracted the height of the predicted tide from the recorded length of pipe out to get the depth to the top of a cored interval. Similarly, at the time drilling finished for a core, we subtracted the predicted tide from the total pipe out to get the depth to the bottom of a cored interval.

[11] Logging data were not corrected for tides. Logging depths were previously depth-shifted on the basis of several fixed peaks: the end of the casing and high NGR intervals (http://iodp.ldeo.columbia.edu/DATA/).

[12] We determined recovery percentages by summing the total length of core pieces recovered and dividing by the cored interval (Table 1). The average piece length is 8 cm (maximum piece length is 148 cm; minimum length was less than 1 cm). Before tide correction 13 of the 233 cores were reported to have >100% recovery, with 11 of those >103% recovery. After tide correction 6 cores had >100%, with only 3 of those >103% (Table 1). Adjusting the top and bottom of each core depth for tides, we significantly reduced the

Table 1. Tide-Corrected Core Depths, Calculated From Total Pipe Out, Mean Water Depth, and Predicted Tidal Height at IODP Hole 1256D[a]

ODP Leg 206 (2002)								Before Tide Corrections		After Tide Corrections
Core	Month	Day	Time EOC (hours)	Pipe Out SOC (mbrf)	Cored (m)	Recovered (m)	Tide (m)	Top (mbsf)	Recovery (%)	Top (mbsf)
2	12	7	0155	3921.5	2.0	1.4	−0.4	276.1	68.9	276.5
3	12	7	0615	3923.5	7.0	4.4	−0.4	278.1	80.9	278.5
4	12	7	1020	3930.5	4.8	5.3	1.1	285.1	84.5	284.0
5	12	7	1400	3935.3	4.8	4.6	−0.3	289.9	126.2	290.2
6	12	7	2210	3940.1	9.2	9.2	0.9	294.7	91.8	293.8
7	12	8	0145	3949.3	9.4	8.4	0.1	303.9	81.2	303.8
8	12	8	0540	3958.7	9.5	8.2	−0.9	313.3	101.7	314.2
9	12	8	0905	3968.2	4.6	5.9	0.5	322.8	137.9	322.3
10	12	8	1215	3972.8	4.5	4.8	0.9	327.4	75.9	326.5
11	12	8	1629	3977.3	9.3	6.3	−1.0	331.9	83.9	332.9
12	12	9	0000	3986.6	9.1	10.1	0.9	341.2	96.8	340.3
13	12	9	0400	3995.7	9.2	3.5	−0.5	350.3	36.8	350.8
14	12	9	0655	4004.9	4.7	3.2	−0.7	359.5	101.6	360.2
15	12	9	1215	4009.6	4.7	3.4	0.9	364.2	63.6	363.3
16	12	9	1430	4014.3	4.6	1.1	0.3	368.9	19.8	368.7
17	12	9	1700	4018.9	4.5	1.1	−0.8	373.5	24.4	374.3
18	12	9	2010	4023.4	4.7	2.4	−0.6	378.0	63.1	378.6
19	12	9	2229	4028.1	4.7	0.4	0.4	382.7	9.3	382.3
20	12	10	0250	4032.8	9.4	1.1	0.4	387.4	10.4	387.0
21	12	10	0710	4042.2	9.2	2.2	−0.7	396.8	27.9	397.5
22	12	11	1210	4051.4	4.3	5.1	0.5	406.0	103.0	405.5
23	12	11	1710	4055.7	9.2	2.1	−0.2	410.3	23.0	410.5
24	12	12	2240	4064.9	9.3	2.9	−0.2	419.5	33.5	419.7
25	12	12	0430	4074.2	9.5	0.7	0.4	428.8	7.6	428.4
26	12	12	1400	4083.7	7.1	7.9	0.5	438.3	96.6	437.8
27	12	12	1935	4090.8	5.5	3.8	−0.5	445.4	78.1	445.9
28	12	13	0030	4096.3	5.7	1.9	0.1	450.9	35.8	450.8
29	12	13	0325	4102.0	4.8	1.6	0.7	456.6	31.0	455.9
30	12	13	0525	4106.8	4.6	0.7	0.4	461.4	12.8	461.0
31	12	13	1200	4111.4	9.2	1.4	−0.2	466.0	14.3	466.2
32	12	13	2025	4120.6	5.8	4.6	−0.5	475.2	90.1	475.7
33	12	14	0640	4126.4	3.4	3.4	0.3	481.0	98.8	480.7
34	12	14	1445	4129.8	4.6	4.6	0.3	484.4	91.9	484.2
35	12	14	2015	4134.4	5.0	2.6	−0.2	489.0	48.7	489.2
36	12	16	0005	4139.4	6.1	2.5	−0.6	494.0	50.1	494.6
37	12	16	0750	4145.5	4.2	5.3	0.5	500.1	126.4	499.6
38	12	16	1755	4149.7	9.2	3.0	0.5	504.3	29.5	503.8
39	12	16	2225	4158.9	4.0	2.7	−0.3	513.5	88.6	513.8
40	12	17	0515	4162.9	7.3	1.0	0.6	517.5	12.5	516.9
41	12	17	1040	4170.2	4.6	2.8	−0.3	524.8	66.2	525.1
42	12	17	1645	4174.8	4.5	2.6	0.1	529.4	57.6	529.3
43	12	17	2150	4179.3	9.2	2.0	0.1	533.9	21.2	533.8
44	12	18	0415	4188.5	9.4	2.6	0.1	543.1	26.1	543.0
45	12	18	1200	4197.9	9.0	1.5	−0.5	552.5	19.6	553.0
46	12	18	2015	4206.9	9.5	3.4	0.6	561.5	33.8	560.9
47	12	19	2229	4216.4	6.0	2.7	0.1	571.0	39.8	570.9
48	12	20	0255	4222.4	5.1	2.2	−0.7	577.0	61.9	577.7
49	12	20	1000	4227.5	9.4	2.2	0.7	582.1	20.7	581.4
50	12	20	1305	4236.9	4.6	1.4	−0.5	591.5	28.3	592.0
51	12	20	1600	4241.5	4.6	2.5	−0.9	596.1	69.1	597.0
52	12	21	2340	4246.1	9.1	2.0	0.2	600.7	24.3	600.5
53	12	21	0955	4255.2	8.3	3.4	0.9	609.8	40.7	608.9
54	12	21	2150	4263.5	9.3	4.3	0.8	618.1	40.8	617.3
55	12	22	0540	4272.8	9.2	2.2	−0.5	627.4	25.3	627.9
56	12	22	1300	4282.0	9.2	4.2	0.1	636.6	46.9	636.5
57	12	22	2015	4291.2	9.2	5.5	0.3	645.8	60.7	645.5

Table 1. (continued)

ODP Leg 206 (2002)								Before Tide Corrections	After Tide Corrections	
Core	Month	Day	Time EOC (hours)	Pipe Out SOC (mbrf)	Cored (m)	Recovered (m)	Tide (m)	Top (mbsf)	Recovery (%)	Top (mbsf)
58	12	23	2115	4300.4	4.0	1.8	0.5	655.0	33.8	654.6
59	12	24	0435	4304.4	9.6	4.9	−0.8	659.0	60.5	659.8
60	12	24	1015	4314.0	9.4	1.9	0.8	668.6	19.3	667.8
61	12	24	1415	4323.4	9.2	1.3	0.1	678.0	14.5	677.9
62	12	24	2150	4332.6	9.3	1.1	0.4	687.2	11.4	686.8
63	12	25	0230	4341.9	4.6	1.3	0.3	696.5	24.5	696.2
64	12	25	0735	4346.5	4.6	2.5	−0.6	701.1	75.6	701.7
65	12	25	1300	4351.1	4.7	3.6	0.8	705.7	56.3	704.9
66	12	25	1855	4355.8	4.4	0.9	−0.9	710.4	32.3	711.3
67	12	26	0110	4360.2	4.7	3.9	0.9	714.8	65.4	713.9
68	12	26	0445	4364.9	4.6	1.5	−0.3	719.5	29.7	719.8
69	12	26	0815	4369.5	4.6	1.2	−0.6	724.1	36.6	724.7
70	12	26	1310	4374.1	4.6	2.2	0.8	728.7	37.1	727.9
71	12	26	1730	4378.7	4.6	1.6	−0.5	733.3	40.3	733.8
72	12	27	2240	4383.3	4.5	2.2	0.1	737.9	57.4	737.8
73	12	27	0335	4387.8	4.8	1.7	0.8	742.4	29.2	741.6
74	12	27	1025	4392.6	4.8	2.3	−0.2	747.2	52.6	747.4
IODP Expedition 309 (2005)								Before Tide Corrections	After Tide Corrections	
Core	Month	Day	Time EOC (hours)	Pipe Out SOC (mbrf)	Cored (m)	Recovered (m)	Tide (m)	Top (mbsf)	Recovery (%)	Top (mbsf)
75	7	19	0815	4397.4	1.9	1.3	0.2	752.0	49.3	751.8
76	7	19	1255	4399.3	4.8	1.3	−0.7	753.9	40.7	754.6
77	7	19	1900	4404.1	4.8	1.8	0.9	758.7	29.0	757.8
78	7	20	0300	4408.9	6.1	3.1	−0.4	763.5	54.1	763.9
79	7	20	0945	4415.0	9.6	2.9	0.0	769.6	29.3	769.6
80	7	20	1535	4424.6	9.6	3.2	−0.2	779.2	37.5	779.4
81	7	20	1940	4434.2	3.4	0.6	1.0	788.8	13.6	787.8
82	7	21	0420	4437.6	7.0	1.5	−0.3	792.2	24.7	792.5
83	7	21	0700	4444.6	2.6	1.5	0.7	799.2	34.7	798.5
84	7	21	1405	4447.2	9.6	2.0	−0.9	801.8	22.9	802.7
85	7	22	2355	4456.8	9.6	7.2	−0.2	811.4	70.4	811.6
86	7	23	0505	4466.4	9.6	3.8	−0.8	821.0	39.1	821.8
87	7	23	1640	4476.0	9.6	3.4	−1.0	830.6	35.5	831.6
88	7	24	0255	4485.6	9.6	1.3	−0.9	840.2	17.1	841.1
89	7	24	0940	4495.2	9.6	0.6	1.1	849.8	5.9	848.7
90	7	24	1225	4504.8	4.8	0.7	0.5	859.4	12.0	858.9
91	7	24	1520	4509.6	4.8	0.9	−0.8	864.2	30.8	865.0
92	7	24	2215	4514.4	4.8	1.2	1.1	869.0	18.6	867.9
93	7	25	0230	4519.2	4.8	0.8	−0.3	873.8	21.8	874.1
94	7	25	1235	4524.0	9.6	1.6	1.0	878.6	15.2	877.6
95	7	25	1455	4533.6	4.8	1.1	−0.2	888.2	31.0	888.4
96	7	26	2340	4538.4	4.8	1.2	1.1	893.0	23.5	891.9
97	7	27	0130	4543.2	4.8	0.9	0.9	897.8	13.2	896.9
98	7	27	0630	4548.0	4.8	0.3	−1.0	902.6	9.3	903.6
99	7	27	1250	4552.8	3.2	2.4	1.1	907.4	47.6	906.3
100	7	27	1805	4556.0	6.4	1.5	−0.7	910.6	28.3	911.3
101	7	28	0320	4562.4	9.6	1.5	0.5	917.0	16.6	916.5
102	7	28	1325	4572.0	9.4	2.5	1.0	926.6	24.3	925.6
103	7	28	1640	4581.4	4.8	0.7	0.3	936.0	12.0	935.7
104	7	28	2205	4586.2	4.8	0.6	−0.5	940.8	14.1	941.3
105	7	29	0415	4591.0	4.8	0.8	0.4	945.6	13.9	945.2
106	7	29	0855	4595.8	4.8	1.0	−0.8	950.4	31.6	951.2

Table 1. (continued)

IODP Expedition 309 (2005)								Before Tide Corrections	After Tide Corrections	
Core	Month	Day	Time EOC (hours)	Pipe Out SOC (mbrf)	Cored (m)	Recovered (m)	Tide (m)	Top (mbsf)	Recovery (%)	Top (mbsf)
107	7	29	1430	4600.6	3.6	0.5	0.9	955.2	13.3	954.3
108	7	30	1755	4604.2	6.0	2.2	0.5	958.8	31.7	958.3
109	7	31	2330	4610.2	4.8	1.8	−0.6	964.8	41.6	965.4
110	7	31	0735	4615.0	4.8	2.9	−0.1	969.6	70.5	969.7
111	7	31	1615	4619.8	4.8	1.0	0.7	974.4	15.4	973.7
112	8	2	0030	4624.6	4.8	1.2	−0.7	979.2	33.3	979.9
113	8	2	0540	4629.4	4.8	1.5	0.4	984.0	29.2	983.6
114	8	2	0920	4634.2	4.8	2.0	0.1	988.8	36.8	988.7
115	8	2	1350	4639.0	4.8	1.1	−0.5	993.6	25.9	994.1
116	8	2	2110	4643.8	4.8	1.4	0.3	998.4	23.5	998.1
117	8	3	0035	4648.6	4.8	1.9	−0.7	1003.2	48.6	1003.9
118	8	3	0520	4653.4	4.8	0.8	0.2	1008.0	17.4	1007.8
119	8	3	0925	4658.2	4.8	0.7	0.3	1012.8	11.9	1012.5
120	8	3	1445	4663.0	4.9	1.4	−0.5	1017.6	37.3	1018.1
121	8	3	1925	4667.9	4.8	1.4	0.7	1022.5	25.8	1021.8
122	8	4	2235	4672.7	4.8	2.1	0.1	1027.3	37.1	1027.2
123	8	4	0230	4677.5	4.8	1.2	−0.8	1032.1	33.9	1032.9
124	8	4	0855	4682.3	4.8	0.7	0.6	1036.9	12.2	1036.3
125	8	4	1240	4687.1	4.8	0.6	−0.5	1041.7	13.0	1042.2
126	8	4	1700	4691.9	4.8	0.8	−0.1	1046.5	15.4	1046.6
127	8	5	1616	4696.7	4.8	0.9	−0.5	1051.3	25.5	1051.8
128	8	5	2120	4701.5	4.8	1.1	0.8	1056.1	17.6	1055.3
129	8	6	0300	4706.3	4.8	2.0	−0.9	1060.9	61.8	1061.8
130	8	6	0950	4711.1	4.8	2.4	0.8	1065.7	39.4	1064.9
131	8	6	1340	4715.9	4.8	2.1	−0.4	1070.5	53.8	1070.9
132	8	6	1950	4720.7	4.8	1.5	0.5	1075.3	27.1	1074.8
133	8	7	0100	4725.5	4.8	1.6	−0.2	1080.1	35.1	1080.3
134	8	7	0730	4730.3	4.8	1.9	0.2	1084.9	38.6	1084.7
135	8	7	1305	4735.1	4.8	1.7	0.0	1089.7	35.9	1089.7
136	8	7	1935	4739.9	4.8	1.2	0.2	1094.5	24.4	1094.3
137	8	8	0120	4744.7	4.8	1.0	0.0	1099.3	21.1	1099.3
138	8	8	0800	4749.5	4.8	2.1	0.2	1104.1	48.1	1103.9
139	8	9	1250	4754.3	4.8	1.6	0.6	1108.9	26.8	1108.3
140	8	9	1845	4759.1	4.8	0.9	−0.5	1113.7	21.9	1114.2
141	8	10	0220	4763.9	4.8	0.7	0.0	1118.5	13.9	1118.5
142	8	10	0725	4768.7	4.8	2.6	−0.5	1123.3	62.5	1123.8
143	8	10	1430	4773.5	4.4	2.2	0.2	1128.1	55.5	1127.9
144	8	11	2250	4777.9	5.0	2.5	0.6	1132.5	39.8	1131.9
145	8	11	0530	4782.9	4.7	2.6	−0.8	1137.5	85.7	1138.3
146	8	11	1200	4787.6	3.0	3.4	0.9	1142.2	98.8	1141.3
147	8	13	1140	4790.6	5.9	1.1	0.4	1145.2	17.4	1144.8
148	8	13	1710	4796.5	5.0	0.7	0.0	1151.1	14.2	1151.1
149	8	14	2330	4801.5	4.2	1.3	0.0	1156.1	27.4	1156.1
150	8	14	0620	4805.7	5.0	0.7	−0.4	1160.3	14.6	1160.7
151	8	14	1125	4810.7	4.6	1.1	0.0	1165.3	24.2	1165.3
152	8	14	1810	4815.3	5.0	0.6	0.0	1169.9	12.8	1169.9
153	8	15	0050	4820.3	4.7	2.4	0.1	1174.9	44.7	1174.8
154	8	15	0805	4825.0	5.0	2.2	−0.5	1179.6	57.0	1180.1
155	8	15	1500	4830.0	4.8	2.5	0.7	1184.6	43.8	1183.9
156	8	15	2000	4834.8	4.8	2.2	−0.3	1189.4	51.9	1189.7
157	8	16	0230	4839.6	4.8	2.3	0.2	1194.2	40.6	1194.0
158	8	16	0905	4844.4	4.8	0.8	−0.5	1199.0	16.8	1199.5
159	8	17	1125	4849.2	4.8	0.8	−0.7	1203.8	23.6	1204.5
160	8	17	1630	4854.0	1.6	1.6	0.6	1208.6	89.0	1208.0
161	8	17	2015	4855.6	3.2	1.7	0.4	1210.2	40.9	1209.8
162	8	18	0210	4858.8	4.8	3.2	−0.6	1213.4	81.6	1214.0
163	8	18	0900	4863.6	4.8	3.4	0.3	1218.2	70.9	1217.9

Table 1. (continued)

IODP Expedition 309 (2005)								Before Tide Corrections		After Tide Corrections
Core	Month	Day	Time EOC (hours)	Pipe Out SOC (mbrf)	Cored (m)	Recovered (m)	Tide (m)	Top (mbsf)	Recovery (%)	Top (mbsf)
164	8	18	1630	4868.4	4.8	2.9	0.3	1223.0	51.9	1222.7
165	8	19	2310	4873.2	4.8	3.5	−0.4	1227.8	99.2	1228.2
166	8	19	0655	4878.0	3.8	3.6	0.9	1232.6	67.7	1231.8
167	8	19	1205	4881.8	5.8	3.2	−0.6	1236.4	77.9	1237.0
168	8	19	2035	4887.6	4.8	5.7	1.0	1242.2	82.9	1241.2
169	8	20	0130	4892.4	4.8	2.7	−1.0	1247.0	97.5	1248.0
170	8	20	0910	4897.2	3.3	3.3	1.0	1251.8	87.8	1250.8

IODP Expedition 312 (2005)								Before Tide Corrections		After Tide Corrections
Core	Month	Day	Time EOC (hours)	Pipe Out SOC (mbrf)	Cored (m)	Recovered (m)	Tide (m)	Top (mbsf)	Recovery (%)	Top (mbsf)
172	11	21	1030	4900.5	5.5	0.2	0.6	1255.1	3.5	1254.5
173	11	21	1505	4906.0	4.8	1.3	−0.1	1260.6	31.0	1260.7
174	11	22	2250	4910.8	5.9	1.2	0.4	1265.4	18.2	1265.0
175	11	22	0450	4916.7	4.8	0.9	−0.4	1271.3	23.4	1271.7
176	11	22	1355	4921.5	4.8	2.0	0.5	1276.1	32.9	1275.6
177	11	22	1910	4926.3	4.8	0.2	−0.7	1280.9	5.9	1281.6
178	11	23	0210	4931.1	4.8	0.5	0.5	1285.7	8.9	1285.2
179	11	23	0715	4935.9	4.8	0.2	−0.5	1290.5	4.5	1291.0
180	11	23	1430	4940.7	4.8	0.1	0.5	1295.3	1.9	1294.8
181	11	23	2015	4945.5	4.8	0.6	−0.6	1300.1	14.5	1300.7
182	11	24	0400	4950.3	4.8	0.4	0.3	1304.9	7.0	1304.6
183	11	25	0920	4955.1	4.8	0.1	−0.5	1309.7	1.3	1310.2
184	11	25	1600	4959.9	1.0	0.9	0.4	1314.5	44.9	1314.1
185	11	25	2130	4960.9	4.0	0.1	−0.5	1315.5	3.0	1316.0
186	11	26	0510	4964.9	4.8	1.0	0.5	1319.5	20.5	1319.0
187	11	26	1420	4969.7	4.8	2.2	0.2	1324.3	42.6	1324.1
188	11	27	0100	4974.5	4.8	0.1	−0.1	1329.1	3.0	1329.2
189	11	27	0800	4979.3	4.8	0.8	0.1	1333.9	17.7	1333.9
190	11	27	1930	4984.1	4.8	0.2	0.2	1338.7	3.3	1338.5
191	11	29	0400	4988.9	4.8	0.1	0.4	1343.5	1.4	1343.1
192	11	29	1445	4993.7	4.8	0.1	−0.4	1348.3	1.8	1348.7
193	11	30	0320	4998.5	4.8	0.1	−0.2	1353.1	0.9	1353.3
194	11	30	1235	5003.3	4.8	0.4	−0.8	1357.9	12.5	1358.7
195	11	30	1810	5008.1	1.0	0.1	0.5	1362.7	2.8	1362.2
196	12	1	0120	5009.1	3.8	0.5	−0.6	1363.7	22.5	1364.3
197	12	2	0850	5012.9	1.5	0.1	1.0	1367.5	2.4	1366.5
198	12	2	1720	5014.4	2.3	0.4	−0.4	1369.0	16.8	1369.4
199	12	3	0045	5016.7	1.0	0.0	−0.4	1371.3	0.0	1371.7
200	12	3	0700	5017.7	0.5	0.0	0.5	1372.3	0.0	1371.8
202	12	8	1730	5018.2	2.0	0.5	−0.4	1372.8	22.8	1373.2
203	12	8	2200	5020.2	2.5	0.1	−0.4	1374.8	5.8	1375.2
204	12	9	0625	5022.7	4.8	0.0	−0.3	1377.3	0.8	1377.6
205	12	9	1815	5027.5	4.8	0.1	−0.2	1382.1	2.3	1382.3
206	12	10	0610	5032.3	3.8	0.2	0.2	1386.9	5.3	1386.7
207	12	10	1635	5036.1	2.0	0.1	0.6	1390.7	3.4	1390.1
208	12	10	2030	5038.1	3.8	0.1	−0.6	1392.7	2.1	1393.3
209	12	11	0320	5041.9	2.1	0.1	0.8	1396.5	3.7	1395.7
210	12	12	0730	5044.0	2.7	0.0	0.5	1398.6	0.0	1398.1
211	12	12	1445	5046.7	2.8	0.0	0.1	1401.3	1.0	1401.2
212	12	12	2115	5049.5	2.0	0.3	−0.2	1404.1	30.2	1404.3
213	12	13	0630	5051.5	4.8	0.5	1.0	1406.1	7.1	1405.1
214	12	13	1135	5056.3	4.8	2.8	−0.8	1410.9	82.9	1411.7
215	12	13	1805	5061.1	2.2	1.8	0.7	1415.7	54.1	1415.0

Table 1. (continued)

IODP Expedition 312 (2005)								Before Tide Corrections	After Tide Corrections	
Core	Month	Day	Time EOC (hours)	Pipe Out SOC (mbrf)	Cored (m)	Recovered (m)	Tide (m)	Top (mbsf)	Recovery (%)	Top (mbsf)
216	12	14	2300	5063.3	3.7	1.3	−0.5	1417.9	40.6	1418.4
217	12	14	0405	5067.0	3.7	0.8	0.1	1421.6	22.3	1421.5
218	12	14	0935	5070.7	4.7	0.4	0.4	1425.3	7.4	1424.9
219	12	14	1600	5075.4	5.0	0.5	−0.4	1430.0	11.8	1430.4
220	12	14	2215	5080.4	4.6	0.9	0.1	1435.0	17.3	1434.9
221	12	15	0310	5085.0	5.0	0.7	−0.6	1439.6	15.7	1440.2
222	12	16	0510	5090.0	4.7	2.0	−0.1	1444.6	44.5	1444.7
223	12	16	1145	5094.7	5.0	2.8	0.0	1449.3	46.2	1449.3
224	12	16	1550	5099.7	4.6	0.1	−0.9	1454.3	1.7	1455.2
225	12	16	2220	5104.3	5.0	0.1	0.7	1458.9	1.7	1458.3
226	12	17	0320	5109.3	4.6	0.1	−0.8	1463.9	3.2	1464.7
227	12	17	1145	5113.9	4.9	2.4	0.3	1468.5	38.0	1468.2
228	12	17	1545	5118.8	4.6	0.0	−1.0	1473.4	0.0	1474.4
229	12	17	2220	5123.4	5.0	0.0	0.8	1478.0	0.2	1477.2
230	12	18	0300	5128.4	4.9	2.6	−0.8	1483.0	80.4	1483.8
231	12	18	0935	5133.3	5.0	5.1	0.9	1487.9	79.4	1487.0
232	12	18	1430	5138.3	4.6	2.0	−0.6	1492.9	45.9	1493.5
233	12	18	1905	5142.9	5.0	0.2	−0.3	1497.5	4.1	1497.8
234	12	19	0120	5147.9	4.6	0.2	0.1	1502.5	4.1	1502.4

[a] Mean water depth is 3645.4 meters below rig floor (mbrf). Predicted tidal height at IODP Hole 1256D from *Egbert and Erofeeva* [2002] and NOAA (National Buoy Data Center Station 32411, available at http://www.ndbc.noaa.gov/station_history.php?station=32411NOAA, 2007); see text. EOC is end of coring; SOC is start of coring.

preexisting problem of pieces from two adjacent cores being assigned identical depths.

[13] After correcting core depth ranges for tides, our next step in physical property data reduction was to omit spurious data, restricting the density values from both the core and log to a reasonable range (2–3.5 g cm^{-3}). Specifically, we eliminated many particularly low GRA and RHOB values (Table 2). The 5722 GRA values below 2 g cm^{-3} are likely a result of incomplete core volume, inevitable for many of the cracked pieces recovered (Figure 4). We interpreted the 498 RHOB values below that threshold to be the result of large fractures in the hole; such values would not be represented in the smaller, coherent recovered core pieces.

[14] Next, because data were collected at a variety of intervals, we rounded all the depths to the nearest centimeter. Multiple passes of the logging tool were made: of the 17,831 RHOB values from the logged interval, 17,363 were at depths with multiple passes (Figure 5). We averaged RHOB values at the same depth (rounded to the nearest centimeter), for 7200 depths. In addition, 468 depths were only sampled once, still leaving us with a large set of log data for consideration in depth-shifting (Table 2).

4. Depth Integration

[15] GRA core data and RHOB logging density data were compared one core at a time, piece by piece, using a simple algorithm in MATLAB (auxiliary material Texts S1–S10[1]), which is summarized briefly in a flowchart (Figure 6). The depth range of a piece was limited using the revised (tide-corrected) core depths in Table 1. The minimum depth of a piece was limited by the top of the core plus the total length of recovered core pieces above, if any. One exception was that a piece was allowed to move up into space that remains after placing the core above, because core material sometimes remains in the core barrel when it is drilled but not removed (standing like a stump). Thus, material recovered from a core could have been drilled during the interval above. The lower maximum depth of a piece was the top of the next core, minus the total length of any deeper pieces, if any, in that core.

[16] For each piece in the core, a maximum GRA value was found. Because few of the cores com-

[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GC002010.

Table 2. Data Summary: IODP Hole 1256D Values Available After Each Step of Preprocessing[a]

Density Measurement	Data From Depth Range (276-1432 mbsf)	Density ≥ 2 g cm^{-3} and ≤ 3.5 g cm^{-3}	After Depth Rounding[b]
GRA (core)	16,903	11,181	11,181
MAD (core)	359	359	359
RHOB (log)	18,329	17,831	7,668

[a] GRA and MAD are core data (Integrated Ocean Drilling Program and Texas A&M University, available at http://www-odp.tamu.edu/database/, accessed 31 December 2007); RHOB measurements are standard wireline log data from the Hostile Environment Lithodensity Sonde (both main and repeat runs (Integrated Ocean Drilling Program and Lamont Doherty Earth Observatory, available at http://iodp.ldeo.columbia.edu/DATA/, accessed 31 December 2007)).

[b] Depth values were rounded to the nearest centimeter. Because of repeat passes in the log, 95% of RHOB values were averages; only 468 data points were the only measurements from a given depth.

pletely filled a core liner, the maximum GRA value for a piece minimizes the influence of the cracked and broken nature of the recovered pieces (especially the ends) that underwent de-pressurization and physical damage from drilling and travel from the subseafloor to the ship. Each piece GRA density value was compared to the RHOB density logging record within the possible depth range for that piece.

[17] In our MATLAB code, finding new depths for as many pieces as possible was more important than minimizing the core-log density difference for any one piece. Any RHOB density value that was within 20% of the maximum GRA density value of the piece and within the depth range was considered a possible match. We found possible matches for nearly every piece of every core (2707 of the 2886 individual pieces had one or more depth matches). When multiple possible depths were selected that fit the requirements above, the new depth was selected as the minimum difference between GRA and RHOB density. Most pieces had multiple depth possibilities (2660 of 2707 pieces); less than 2% (47 pieces) had only one core-log depth match. Finally, for pieces with either no log values within the range of depth possibilities (138 pieces) or no RHOB value within 20% of the piece maximum GRA value (41 pieces), a depth was assigned directly below the piece above it. If two equally likely scenarios arose, where the same number of pieces within a core matched with the same differences between GRA and RHOB densities, the more shallow depths were arbitrarily assigned (Data Set 1).

5. Evaluation of New Depths

[18] Using the original and newly revised depths given in Data Set 1, we compared additional core data from Hole 1256D to determine the correlation between core and logging data before and after the depth shifting. Core data (MAD) came from measurements made on minicubes taken from the core pieces described in section 2. We used the revised piece depths (Data Set 1) to find revised depths for the minicubes (Figure 2). We then compared the MAD density values to the nearest RHOB density values from the logging record (Figure 7).

[19] We compared the data, both before depth shifting and after depth shifting (Figure 8). Before depth shifting, the average difference between MAD and RHOB values at the same depth was 0.06 g cm^{-3}, as compared to 0.02 g cm^{-3} for after depth shifting. A paired t-test comparing the differences before and after shifting yields a small p value (0.0002), indicating that the two averages are significantly different.

6. Discussion

[20] In sediments, recovery from drilling can frequently be near 100% and multiple holes can be used to cross-correlate several physical properties for a nearly continuous core-log integrated record. The depth-shifting method presented here, for poor-recovery igneous rocks, is a first attempt at integrating core pieces with the logging record from IODP Hole 1256D. In our first step, just by adjusting the top of each core depth for tides, we nearly eliminated the preexisting problem of pieces from two adjacent cores being assigned identical depths. Although local tide data were not available during coring, data from Buoy Station 32411 (04°55′N × 090°42′W) show good agreement with the predictions after buoy installation in March 2007 (NOAA, National Buoy Data Center Station 32411, available at http://www.ndbc.noaa.gov/station_history.php?-station=32411, accessed 31 December 2007). Future drilling and logging at this site could take advantage of real-time tide data.

[21] Our depth-shifting method is simple, but with such simplicity comes limitation. Physical properties

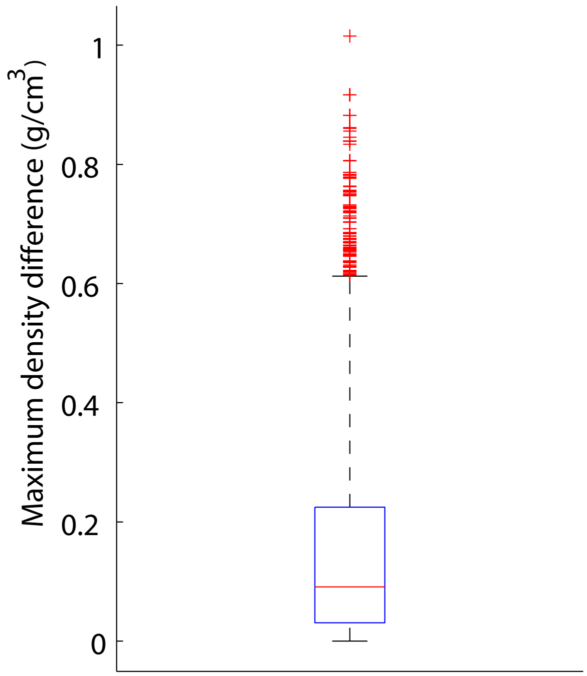

Figure 5. Box plot of the maximum density difference between duplicate measurements of RHOB at a single depth from multiple logging passes. The mean density difference for each depth that had multiple passes is 0.15 g cm^{-3}, with a maximum of 1.03 g cm^{-3} and a minimum of 0 g cm^{-3}. The box is the interquartile range (the middle 50% of data lie within). The horizontal line within the box is the median. The whiskers are drawn to the furthest data points within twice the interquartile range. The red crosses are outliers (greater than twice the interquartile range).

are made at different scales in the core and logging records. Cores preferentially sample high-density sections of the crust, which are among the more coherent and durable sections of the logged open hole. Fractures, cavities, and rubbly portions of the crust may be measured in the open hole but are not recovered by drilling. To better understand the bulk properties of ocean crust, it is important to consider these non-recovered intervals. For our purposes, we were limited to comparing the more coherent intervals of the logged hole with recovered core.

[22] IODP Hole 1256D has the distinction of being the first drilled to gabbro in normal ocean crust and offers us a unique view into the subsurface. Com-

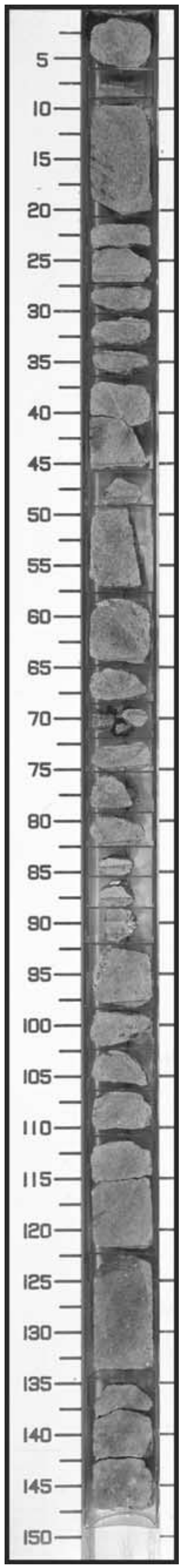

Figure 4. Core 216 from IODP Hole 1256D, with ~41% recovery, is an example of the fractured nature of recovered core from drilling igneous crust. Scale is in centimeters. (Modified from http://www-odp.tamu.edu/database/.)

paring physical properties data as well as petrologic, structural, geochemical, and other information from the core and log will aid our understanding of the physical and chemical processes that control formation and evolution of ocean crust. Such integration of data as well as visual core-log integration will advance our understanding of these controlling processes at multiple scales of measurements.

7. Summary

[23] Assigning the shallowest possible depths for drilled core pieces is a quick, but less than optimal method of determining in situ depth, especially where recovery is poor. Thus, we present here a revised depth vector for the pieces of IODP Hole 1256D, first corrected for tides by core and then adjusted for data correlation by piece. The new depth vector results in greater agreement between

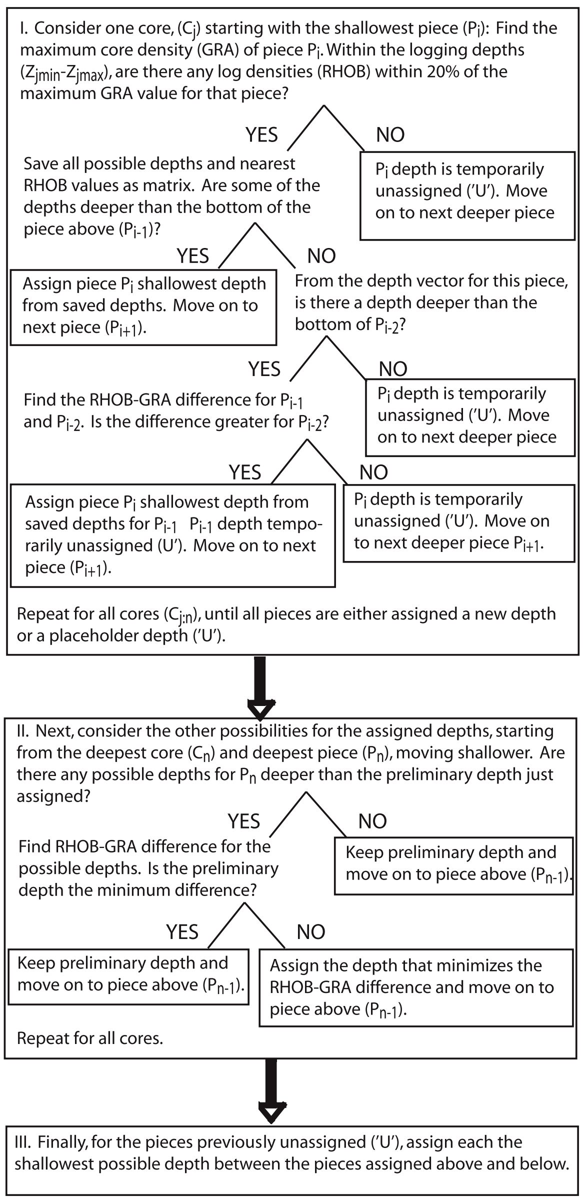

Figure 6. Flowchart describing how the MATLAB function CORELOGINTEGRATE depth-shifts with density data from the core (GRA) and log (RHOB).

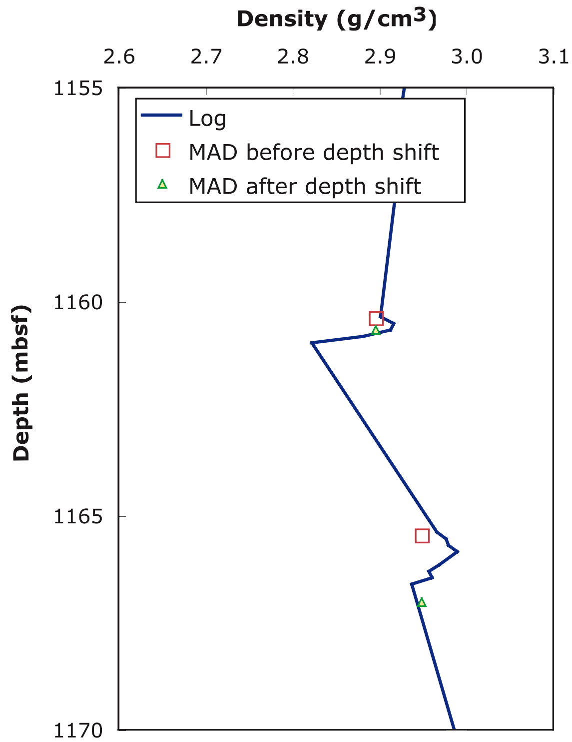

Figure 7. Example of depth-shifting for two pieces.

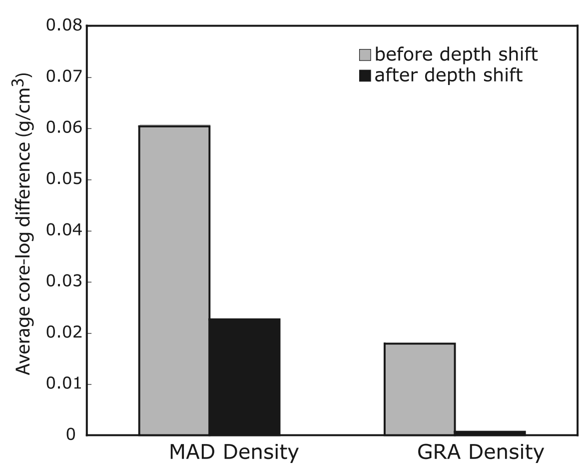

Figure 8. Average core-log difference before and after depth-shifting for the MAD density and GRA density data. Depth-shifting significantly improves the agreement between the log and MAD data and the log and GRA data.

core and log physical properties data. This improvement of depths will likely be helpful to other researchers integrating core and logging data in this first hole drilled through intact, in situ ocean crust. Our method has the advantage of being rapid, requiring little subjective input, and being applicable to any core-log integration problem where sufficient data have been collected in both the open hole and from the recovered core. Depth-shifting is a reasonably quick, automatic method for adjusting core piece depths in drilling-based studies of the ocean crust, and other drill holes on land and undersea.

Acknowledgments

[24] This research used samples and data provided by the Integrated Ocean Drilling Program (IODP). Funding for this research was provided by a JOI/USSSP Post-Expedition Award to L.A.G. Mick Spillane of the NOAA Center for Tsunami Research provided tide calculations using OSU TPXO6.2. This manuscript was improved by input from Susan Schnur and the thoughtful reviews of Peter Blum, Matt O'Regan, and Damon Teagle. Paula Clark (sadly now deceased) contributed to an early version of this method.

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